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Towards site-specific management of invasive alien trees based on the assessment of their impacts: the case of *Robinia pseudoacacia*

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Abstract

Robinia pseudoacacia L. (black locust) is a North American tree, considered controversial because of the conflict between multiple uses by humans and negative environmental impacts, which have resulted in it being listed among the most invasive species in Europe. The current management of *Robinia* stands in Central Europe varies locally according to national legislation, preferring either socio-economic benefits or biodiversity impacts.

We collected field data from our target region of Czechia, reviewed research articles including local grey literature mostly from Central and Southern Europe, unpublished results of local projects and inquired relevant specialists. Because *Robinia* grows in habitats ranging from urban to forest to natural grassland, neither unrestricted cultivation nor large-scale eradication is applicable as a universal practice. In this paper we suggest a complex management strategy for *Robinia* stands that takes into account habitat, this species' local ability to spread, as well as economic, cultural and biodiversity aspects.

We categorized *Robinia* stands growing in Europe into eight groups and proposed stratified approach to the management based on decisions that reflect local context. Depending on that, the management includes (i) establishment of new plantations, (ii) maintenance or utilization of existing stands, (iii) tolerance and (iv) conversion to original vegetation.

Our complex management strategy will provide a comprehensive guideline for the management of alien trees in Europe.

Keywords

Alien trees, *Robinia pseudoacacia*, plant invasion, nature conservation, management strategies, socio-economic benefit

Introduction

Tree species provide economic, cultural and ecological benefits to humans, often outside their native range. On the other hand, many alien trees have naturalized, subsequently become invasive and have negative environmental impacts in their introduced range. This conflict between positive and negative effects on ecosystem services poses a problem worldwide (e.g. Richardson and Rejmánek 2011, Dickie et al. 2014, Kuebbing and Simberloff 2015, Woodford et al. 2016). *Robinia pseudoacacia* is an example of such controversial tree species (Pergl et al. 2016c, Vítková et al. 2016, 2017). It is a fast growing nitrogen-fixing tree native to the south-eastern part of North America (Fowells 1965), which is planted in temperate regions worldwide (Keresztesi 1988, Li et al. 2014). Its wide utilization in native and introduced ranges started in the second half of 18th century. *Robinia* was originally planted for timber production as it is fast growing and its wood is water- and rot-resistant, and can be used as firewood or to erosion control (Vadas 1914, Göhre 1952). Large-scale afforestation campaigns were organized at the state level across Europe in the late 19th and early 20th centuries (Vítková et al. 2017). Planting and propagation of *Robinia* seemed to offer a remedy for the significant problems with deforested landscape, especially large areas of infertile pastures. Nowadays, it is the second most common broadleaved introduced tree (after *Quercus rubra*) used for forestry and wood production in Europe (MCPFE 2007). Soon after its introduction to Europe it also started to be used for amelioration, reclamation of disturbed sites, leaf forage, biomass production, honey production and shading (Papanastasis et al. 1998, Rédei et al. 2008, Yüksek 2012). Moreover, the tree is convenient for planting in urban or industrial areas, due to its tolerance of air pollution, drought, toxic, salty or nutrient-poor soils (Hillier and Lancaster 2014).

Robinia is listed among 40 most invasive woody angiosperms in the world (Richardson and Rejmánek 2011), categorized as highly invasive in several databases (EPPO, ISSG, DAISIE, CABI), ranked among the top 26 plant species in Europe with highest negative impact (Rumlerová et al. 2016) and mentioned in national Black Lists in many countries (e.g. Botta-Dukát and Balogh 2008, Celesti-Grapow et al. 2009, Vinogradova et al. 2010, Gederaas et al. 2012, Jogan et al. 2012, Seitz and Nehring 2013, Pergl et al. 2016c). The same properties that make *Robinia* attractive for cultivation are the source of problems in nature conservation and environmental management (Matus et al. 2003, Kleinbauer et al. 2010, Ivajnšič et al. 2012, Vítková et al. 2017), i.e. nitrogen fixation ability, a broad habitat tolerance, fast growth and excellent propagation ability, resulting from both prolific seed production and intensive vegetative sprouting (Batzli et al. 1992, Cierjacks et al. 2013, Vítková et al. 2015, Crosti et al. 2016).

Whereas its favourable qualities were appreciated early, the local invasions by *Robinia* started to be widely recognized only after ~1950 (Berg et al. 2016). Until then it was considered as a common naturalized tree (Hegi 1924) whose negative impacts following escape were not perceived as a problem. In traditionally deforested areas such as the Pannonian basin or Czech lowlands, *Robinia* became the main woody species planted in various habitats. It occupied the niche of local native trees, such as oaks,

and replaced them in terms of importance both in the landscape and local economy. The lag between economic acceptance of *Robinia* and its rejection for impact on biodiversity took almost two centuries (Vítková et al. 2017). This period was crucial for its broad acceptance by the public. This tree became popular for its cultural value, evident from its mention in songs, poems, literature and culinary recipes (Vítková et al. 2017). Across Europe, *Robinia* is currently considered to be an integral part of the landscape and not perceived as alien by the public (Fischer et al. 2011, Lindemann-Matthies 2016). In Hungary, it is even an unofficial national tree (Keresztesi 1988). These facts demonstrate that the assessment of *Robinia* as a noxious invader needs to be balanced with its integration into landscapes and wide social acceptance.

In the last decade, the environmental and economic impacts of *Robinia* provoked stormy public debates in Europe, which involved politicians, researchers, nature conservationists, land managers, foresters, beekeepers and horticulturalists, and were recently fueled by proposal for inclusion *Robinia* on the list of invasive alien species (IAS) of Union concern (Commission Implementing Regulation 2016/1141 of 13 July 2016 pursuant to Regulation No 1143/2014 of the European Parliament and of the Council; Genovesi et al. 2015, Lehtiniemi 2016, Pergl et al. 2016a, Vítková et al. 2017), because of its impact on biodiversity, ecosystem services and human health. Unlike species with unambiguously negative environmental and/or economic impacts, *Robinia* found many defenders, who appreciated mainly its economic benefit (Tobisch and Kottek 2013). On the other hand, removing *Robinia* from the first list of perilous invaders of EU concern would compromise the ability to control this species wherever it is necessary. According to the Article 12 (the same Regulation), *Robinia pseudoacacia* may be listed in a national list of IAS of Member State concern. The control of *Robinia* invasion is even more complicated if it is not included as IAS within the legislation of the country (as in e.g. Hungary, Poland and Slovakia) and its regulation is governed by many individual enactments. Sitzia et al. (2016) highlight the potential contribution of the European forestry sector for efficient and effective implementation of EU Regulation and for controlling the spread of invasive alien species in forests. The Code of Conduct on Planted Forest and Invasive Alien Trees is voluntary and applies only to forest plantations (Brundu and Richardson 2016).

Currently, most management tools have been created for specific invaders/regions and are thus often not sufficient to address the complex range of invasion scenarios (Nielsen and Fei 2015). Our new methodological approach will provide a comprehensive guideline for the management of alien trees in Europe. We chose *Robinia pseudoacacia* as a model species because it is abundant and commonly planted, and has a great impact, both commercially and environmentally. The literature on *Robinia* is mostly one-sided, either exclusively economic or ecological. If an article deals with its utilization, it mostly lacks any consideration of the ecological problems (Rédei et al. 2008, Grünewald et al. 2009, Medinski et al. 2014), whereas if it is focused on the *Robinia* invasion, it often avoids any consideration of the economic or cultural interests (Dzwonko and Loster 1997, Kleinbauer et al. 2010, Ivajnšič et al. 2012). Here we reviewed the ecological and socio-economic impact of *Robinia* (Vítková et al. 2017)

to obtain a comprehensive perspective of the invasion by this alien species in Europe. Building on the previous review (Vítková et al. 2017) we suggest a complex management strategy for *Robinia* that takes into account habitats, its ability to spread locally, as well as economic and biodiversity aspects of this invasion. Our main objectives are (i) to categorize *Robinia* populations based on their source, vegetative structure, invaded habitat, possible economic use and environmental risks, (ii) to propose site-specific management on the basis of such categorization and (iii) to compare specifics of the treatment of *Robinia* in different countries and by different stakeholders.

Material and methods

Study species

Robinia pseudoacacia L. (black locust) is a tree, but as a heliophilous and short-lived species, it is a weak competitor. This limitation is balanced by its easy and fast propagation (mainly through root suckers), tolerance of disturbance, rapid growth and tolerance of a wide range of habitats including extreme conditions. On the other hand, *Robinia* is robust and persistent, therefore it is able to persist in a site once colonized for several decades largely independent of the environment, which the tree itself modifies by changing the availability of nutrients in the soil and light conditions (Pyšek et al. 2012, Chytrý 2013, Vítková et al. 2015, Schiffleithner and Essl 2016).

Current landscape is characterized by habitat fragmentation which causes large areas of ecotones and boundary line stands, i.e. optimal conditions for *Robinia*. Serious large-scale disturbances (e.g. mining) provide a lot of open, well aerated and nutrient-rich substrata. Rotation of such disturbance events resulting in decades of successional development at abandoned sites enables *Robinia* to spread, establish and play a key role in succession. Moreover, transport of large volumes of soil containing *Robinia* propagules effectively compensates for the low ability of its large seeds to disperse over great distances.

Study area

Although most data comes from Central and Southern Europe, we considered for our assessment the whole of Europe (Table 1). Czechia (the Czech Republic) was used as the model area for the description of the management approaches as there is a lot of field data for this country (Vítková and Kolbek 2010, Vítková et al. 2015, 2016, 2017, our unpublished data) and *Robinia* is included in the Black List of IAS (Pergl et al. 2016c). We used also some data on the consequences of its planting from other parts of the world (e.g. China – Zhang 2014, Kou et al. 2016; Korea – Lee et al. 2004, Kolbek and Jarolímek 2008) to extend the applicability of suggested management strategies.

Table 1. Selected references from different European countries used for categorization and complex management strategy of *Robinia* stands. See Table 2 for description of categories indicated in the second row.

Phytosociological data	*Robinia* forests	Human-made habitats	Vulnerable habitats	Intensive short rotation plantations
	(Categories 1, 2, 3)	(Categories 4, 8)	(Categories 5, 6)	(Category 7)
Pócs (1954)	Keresztesi (1988)	Bellon et al. (1977)	Frantík (1985)	Papanastasis et al. (1998)
Jurko (1963)	Hruška (1991)	Šindelářová (1986)	Rothröckl (1986)	Platis et al. (2003)
Fekete (1965)	Benčať (1995)	Kunick (1987)	Halassy et Török (1996)	Vasilopoulos et al. (2007)
Bogojevic (1968)	LIFE99 NAT/IT/006252	Kowarik (1990, 1992, 1994, 1996)	Kelemen et Warner (1996)	Oravec (2008)
Hoff (1975)	Essl and Hauser (2003)	Swierkosz (1993)	Čechová (1998)	Rédei et al (2008)
Ščepka (1982)	Führer (2005)	Prach (1994)	Essl et Hauser (2003)	Grünewald et al. (2009)
Klauck (1988)	Novák (2005)	Sukopp and Wurzel (2003)	Matus et al. (2003)	Rédei and Veperdi (2009)
Hruška (1991)	Kalmukov (2006)	Zerbe et al. (2003)	LIFE04 NAT/CZ/000015	Kohán (2010)
Oberdorfer (1992)	LIFE08 NAT/E/000072	Kowarik and Langer (2005)	LIFE05 NAT/H/000117	Böhm et al. (2011)
Swierkosz (1993)	LIFE08 NAT/RO/000502SFC	Pietrzykowski and Krzaklewski (2006)	LIFE06 NAT/SK/000115	Rédei et al. (2011)
Kowarik and Langer (1994)	Rédei et al. (2008, 2012, 2014)	Grünewald et al. (2009)	LIFE07 NAT/B/000043	Kellezi et al. (2012)
Arrigoni (1997)	Motta et al. (2009)	LIFE11 ENV/FR/000746	LIFE07 NAT/D/000213	Stolarski et al. (2013)
Šimonovič et al. (2001)	Schneck (2010)	Yüksek (2012)	Tylč (2007)	Ciccarese et al. (2014)
Oprea (2004)	Bělař (2011)	Vlachodimos et al. (2013)	Böcker and Dirk (2007)	Medinski et al. (2014)
Benčaťová and Benčať (2005, 2008)	Essl et al. (2011)	Kanzler et al. (2015)	Bogdan (2008)	Manzone et al. (2015)
Dakskobler (2007)	Kutnar and Kobler (2013)	Wojda et al. (2015)	LIFE08 NAT/PL/000513	Wojda et al. (2015)
Willner and Grabherr (2007)	Radtke et al. (2013)	Sjöman et al. (2016)	Šefferova-Stanova et al. (2008)	Crosti et al. (2016)
Wilhalm et al. (2008)	Terwei et al. (2013)		LIFE09 NAT/IT/000118	
Campos (2010)	Ciuvăt et al. (2015)		LIFE09 NAT/CZ/000363	
Vítková and Kolbek (2010)	Malvolti et al. (2015)		Bělohlávková (2014)	
	Wojda et al. (2015)		Silva et al. (2014)	
	Akatov et al. (2016)		Schmiedel et al. (2015)	
	Budău and Timofte (2016)		Pergl et al. (2016b)	
	Sytnyk et al. (2016)		Vítková et al. (2016, 2017)	

Phytosociological data	*Robinia* forests	Human-made habitats	Vulnerable habitats	Intensive short rotation plantations
	Kadunc (2016)			
	Kou et al. (2016)			
	Schiffleithner and Essl (2016)			
	Sitzia et al. (2016)			
	Vítková et al. (2016)			

Source of data

Information for our paper, illustrating the approach for a major IAS in our study area, was obtained from (i) more than 100 research articles and local papers referring or applicable mostly to European countries (Table 1), (ii) hundreds of phytosociological relevés of *Robinia* stands growing in Europe (Table 1), (iii) inquiries addressed to European specialists (see Acknowledgments) in nature conservation, invasion ecology and management of *Robinia*, (iv) tens of results of local projects (often unpublished) testing different methods of *Robinia* removal and aftercare (e.g. Halassy and Török 1996, Novák 2005, Böcker and Dirk 2007, Tylč 2007, Bogdan 2008, Bělař 2011, Bělohlávková 2014); (v) practical experience of Czech private companies and administrations of protected areas involved in *Robinia* management, including unpublished data (e.g. Čechová 1998, Veverková 2009), and (vi) our unpublished long-term research on the ecology and impact of *Robinia* stands in various European countries. Although it might seem that there is a great body of quantitative data on, e.g. yield, growing stock, forest regeneration or eradication, in fact the available information is surprisingly poor and rather gappy. Moreover, it does not allow for comparing among individual categories of *Robinia* stands in our model area of Czechia, and even less so in other European countries. The total growing stock and yield of both planted and spontaneous *Robinia* stands could be determined only on forest land belonging to the state (not private owners) in some countries. *Robinia* stands growing on non-forest land, such as on arable land, in parks, urban and mining areas are mostly planted for other purpose than economic profit, therefore both their extent and biological parameters are not known. *Robinia* stands growing in protected areas are usually only monitored in a preparatory phase for eradication. For these reasons, it is not possible to make a rigorous statistical analysis of our general model.

Principles of the stratified approach

According to Dickie et al. (2014) we consider a dichotomy between positive and negative effects on ecosystem services resulting from planting of *Robinia* which currently causes conflicts of interest between different groups of stakeholders (e.g. nature conservation, forestry, urban landscaping, beekeepers and the public). These conflicts are often viewed only in a local context therefore we propose a complex management strategy on European level taking into account both economic benefits and environmental risks associated with *Robinia* cultivation (van Wilgen and Richardson 2014). Based on Holmes et al. (2008), Shafroth et al. (2008) and Gaertner et al. (2016), we suggest practical decision framework for sustainable *Robinia* management (Figure 1). Such framework has to be based on rigorous cost-benefit analysis (Naidoo et al. 2006, Hanley et al. 2009), leading to identification of potential conflicts. At first the potential threats associated with the presence of *Robinia* have to be identified, including threats resulting from inappropriate management of stands. If no conflict is identified, a standard management should

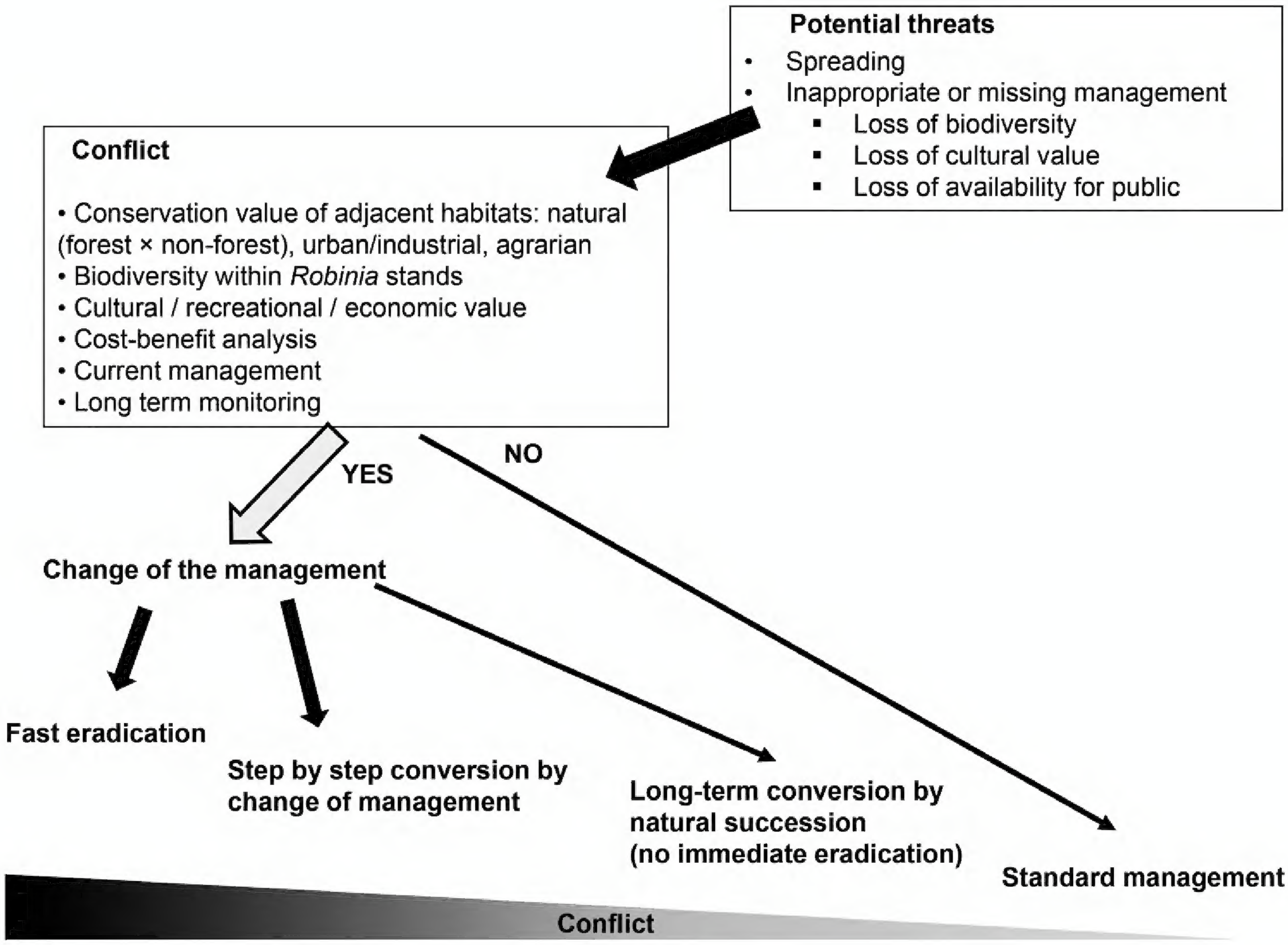

Figure 1. Decision framework for selecting suitable *Robinia* management. Width of arrows indicate importance of the management. Shading indicates the number of potential sites covered (white – relatively few occurrences, black – most of the sites). Data come from the reviewed literature and project reports.

continue (management of plantations, ornamental trees). In presence of any conflict the recommended management depends on the intensity of the threat ranging from slow conversion by succession to fast eradication. In addition, the decision scheme needs to be accompanied by categorization of stands with *Robinia* into eight groups (Table 2) reflecting the variation in habitat conditions and character of stands, in order to make context-dependent decisions relevant to local conditions. For each group, the distribution and source of *Robinia*, its history, ecological characteristics (habitat, structure, plant composition) and currently used management are summarized.

Results and discussion

Categorization of *Robinia* stands according to their management and impact

Based on links between ecological traits such as habitat, vegetation structure, origin, utilization, benefits and environmental risks we distinguish eight types of *Robinia* stands (Table 2). Each type includes four management practices, which are effective in various combinations depending on local conditions: (i) establishment of stands,

Table 2. Main features used in categorization of types of *Robinia* stands, their description and management.

Robinia type	Physiognomy	Distribution and habitats	Source of occurence	Vegetation structure and dynamics	Status	Management
1. Regularly managed *Robinia* forests	Closed forests in natural habitats	Common, temperate and warm areas across Europe	Cultural (open habitats on initially infertile soils threatened by soil erosion, mainly sands and rocky pastures)	Monospecific tree layer	Sustainable - profitable - risky	Forestry maintenance
		Wide range of habitats (from wind-blown nutrient poor sands to the most fertile soils)		Dense and species-rich undergrowth dominated by nitrophilous herbs or grasses		Conversion is troublesome and risky
			Spontaneous (open habitats in the vicinity of plantations, e.g. abandoned vineyards, orchards and fields)	Regular regeneration (forestry)		
2. Regularly managed mixed *Robinia* forests		The most common forest type with *Robinia*	Cultural (open woodlands, gappy forests, clearings, deforested sites)	Mixed - *Robinia* combines with alien and native trees	Sustainable - profitable - low risk	Forestry maintenance
		Wide range of habitats across Europe	Spontaneous (drier parts of floodplain forests, forest margins, disturbed sites)	Biodiversity of undergrowth depends on the share of *Robinia* and other aliens		Conversion is troublesome and risky, succession to natural forests is easy
				Regular regeneration (forestry)		
3. Unmanaged old *Robinia forests*		Czechia, Switzerland	Abandoned old cultures (over 50 years)	Mixed - *Robinia* gradually replaced by competitive trees (*Fraxinus excelsior, Acer platanoides*)	Instable - not profitable - risky	Conversion is troublesome and risky, succession to natural forests is easy
		Less accessible sites, e.g. steep slopes	Spontaneous old and never managed stands, e.g. in rocky ravines	Spontaneous succession without management for several decades		

Robinia type	Physiognomy	Distribution and habitats	Source of occurence	Vegetation structure and dynamics	Status	Management
4. Stands in human-made habitats	Small-scale or semi-open non-forest stands	Common, widespread across Europe	Cultural (ornamental purposes, apiculture or biological recultivation)	Monospecific or mixed stands with native pioneers, nitrophilous trees and aliens	Sustainable - context dependent risk and profit	Context dependent planting or conversion
		Urban, agrarian and industrial areas	Spontaneous (escape and succession in wasteland, public greenery, post-mining landscape and landfills)	High share of aliens in canopy or understory; many ornamental woody species		
		Mining areas		Ruderal undergrowth; diverse dynamic		
5. Dwarf Robinia stands growing in natural grasslands		Pannonian lowland, South and South-East Europe	Unsuccesfull cultivation combined with spontaneous spread	Low, twisted trees (ca 5-10m) or shrubs with native xerophilous shrubs	Sustainable - not profitable - low risk	Conversion / removal is troublesome, risky and mostly not necessary
		Dry habitats (mostly mosaic of grassland, shrubs and open woodland)		Many species of sunny open habitats; nitrophytes are rare due to drought		
				Stable stands; survival of rare species preserves local biodiversity in agricultural land		
6. Young *Robinia* stands spreading into vulnerable habitats		Dry to mesic grasslands across Europe	Spontaneous spread by root suckers from adjacent stands	Young shoots with increasing cover	Instable - not profitable - risky	Conversion / removal is troublesome and risky but necessary
		Rare vulnerable native habitats		Valuable herbaceous vegetation is replaced by *Robinia*		
				Instable stands		

Robinia type	Physiognomy	Distribution and habitats	Source of occurence	Vegetation structure and dynamics	Status	Management
7. Intensive short rotation plantations	Biomass cultures	Across South and Central Europe – e.g. Albania, Austria, Italy, Germany, Greece, Hungary, Poland, Slovakia and Spain	Cultural	Monospecific, low height (average 5-6m), rapid regeneration	Instable - profitable - risky	Intensive cultivation
		Both in forests and arable land		Low biodiversity value, weeds or nitrophytes prevail		Conversion of abandoned plantations to forest
8. Cultivated single trees and avenues	Separate tree individuals	Common across Europe	Cultural	Horticultural treatment, protection of old monument trees	Sustainable - context dependent risk and profit	Context dependent planting or conversion

(ii) maintenance of the existing state or utilization, (iii) tolerance of natural succession without major human interventions, and (iv) conversion, i.e. management or measures targeted at changing a stand into another unit or type of vegetation. The advantages and risks of particular management practices are discussed in the context of different initial conditions. Relations among the types of *Robinia* stands distinguished, successional trends and suitable management practices are shown in Figure 2.

1. Regularly managed *Robinia* forests (Table 2, Figures 2, 3A)

Deep, well-aerated, nutrient-rich mesic soils in warm areas are optimal for the growth of *Robinia* since trees reach up to 35 m, form straight trunks and provide high-quality timber (Figure 3A). However, most *Robinia* forests are in dry habitats such as nutrient-poor sandy or rocky pastures on originally infertile soils threatened by soil erosion (Vadas 1914, Hegi 1924, Göhre 1952, Kolbek et al. 2004), where trees hardly reach 10 m and are often used for firewood or making poles (Vítková and Kolbek 2010, Vítková et al. 2015, 2017). In wooded areas, light-demanding *Robinia* does not spread into dense forests, but is able to colonize forest margins or disturbed sites, such as fresh clear-cuts or post-fire sites. Spontaneously, it spreads also into other open habitats in the vicinity, for example abandoned vineyards, orchards and fields.

Biodiversity value of such *Robinia* forests is mostly low, however, certain groups of organisms prefer them (e.g. macrofungi or habitat generalists among birds; Ślusarczyk 2012, Hanzelka and Reif 2015a, 2015b). The undergrowth is often dense and rich in species (~20 to 45 plant species/200 m^2, similar to that in climax forests), but it is dominated by widely distributed nitrophilous species sharing a wide range of nemoral and ruderal habitats, e.g. *Bromus sterilis*, *Galium aparine*, *Urtica dioica*, *Hedera helix* and *Sambucus nigra.* Species-poor *Robinia* forests growing in dry habitats are dominated by grasses, the dense cover of which may slow down the establishment of native trees.

Establishment and maintenance: Most European production of *Robinia* wood comes from these plantations. In the Pannonian basin in particular they are the main type of forest and their yield varies between 80 and 280 m^3/ha and have an average rotation age of 30 years (Rédei et al. 2008). New stands are still being established, for example in Hungary, Italy and Romania (Rédei et al. 2008, 2012, Enescu and Dănescu 2013, Ciuvăt et al. 2015, Meloni et al. 2016) but not in Czechia, Poland and Switzerland (e.g. MZE 2014, Wojda et al. 2015). Producing saplings from seed is a relatively simple and low cost method, although germination must be facilitated by mechanical scarification (Rédei et al. 2012), soaking in concentrated sulphuric acid or boiling water (Huntley 1990). Propagation from root cuttings is suitable for producing articular clones or special cultivars (Keresztesi 1988, Rédei et al. 2012). Regeneration from root suckers produces a higher yield than from seedlings at a harvest age of 35–37 years. *Robinia* forests need more management than climax tree species (e.g. oaks), as without regular silvicultural treatments the quality of wood deteriorates due to an unshaped crown and deformed trunk (Bělař 2011, Rédei et al. 2012).

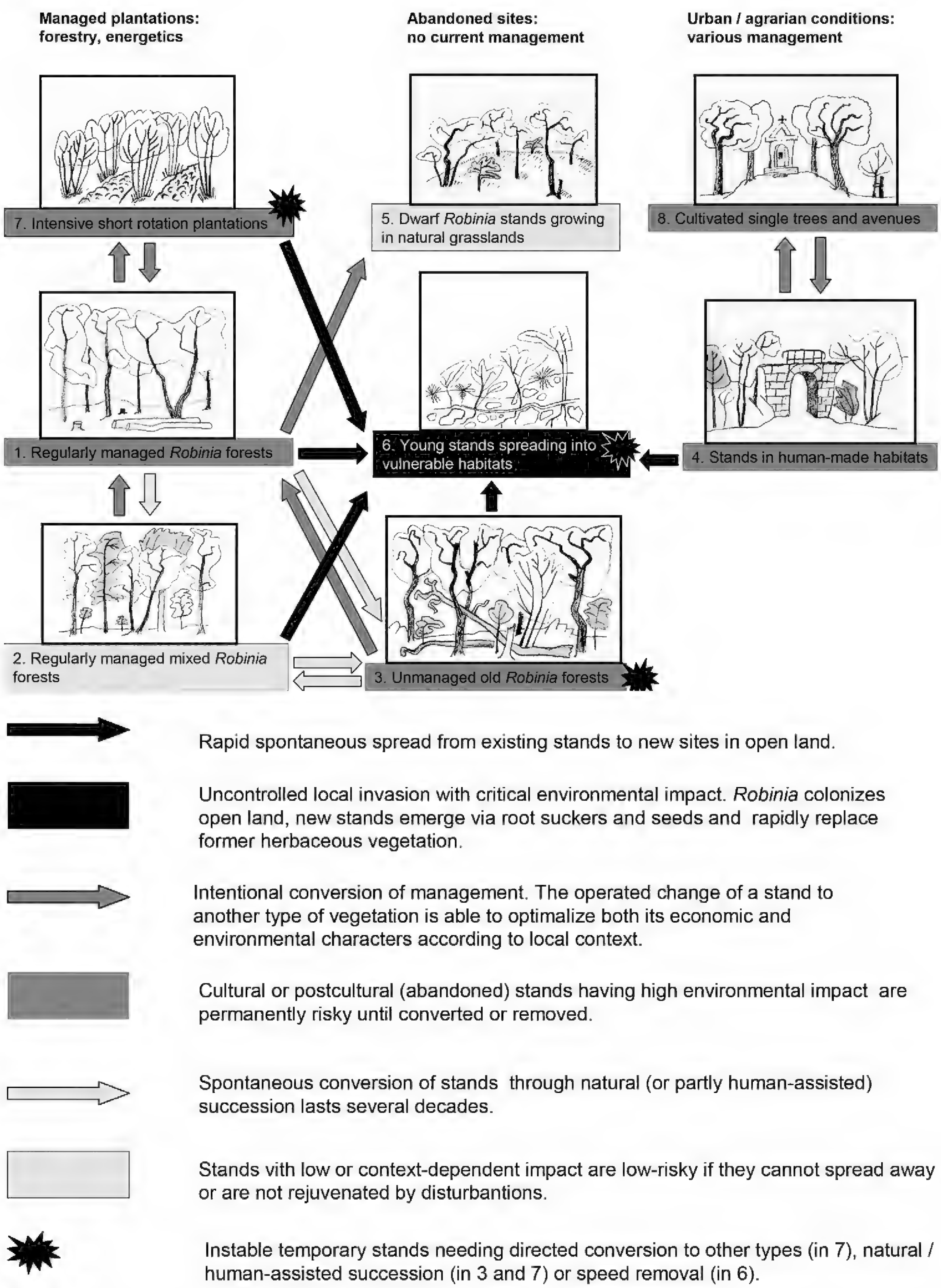

Figure 2. Main successional / intentional dynamic changes among the types of *Robinia* stands. Numbers of vegetation units correspond to stand categorization in the text.

Figure 3. Closed forests in natural habitats (**A–C**) and small-scale stands in man-made habitats (**D**). **A** *Robinia* forest regenerating and managed by coppicing in stripes **B** Planted mixed forest with native *Fraxinus excelsior* and alien *Robinia pseudoacacia* **C** Old *Robinia* forest overgrown by *Fraxinus excelsior* and *Acer platanoides* as a result of spontaneous succession **D** A spontaneously established mixed stand with *Robinia* growing in a quarry.

Tolerance of natural succession: Not remarkable due to economic value of these forests.

Conversion: Restoration of native vegetation is mostly not profitable, being costly and time-consuming. Because of the high sprouting ability of *Robinia*, it is very risky to stop eradication before totally removing all sprouts (Novák 2005, Pergl et al. 2016b, Vítková et al. 2017). There is nothing to be gained by restricting conventional silviculture, especially in early deforested lowlands or suburban zones where *Robinia* has been domesticated for a long time, forms extensive stable metapopulations and where native trees suitable for afforestation are lacking and there are no issues with nature conservation. However, establishment of new stands must be specially assessed, notably those to be established in close proximity of dry or mesic open natural habitats, due to the high sprouting ability of *Robinia*.

2. Regularly managed mixed *Robinia* forests (Table 2, Figures 2, 3B)

Admixture of *Robinia* with cover of up to 10% is the most common type of its occurrence (Vítková et al. 2017). It is a frequent spontaneous admixture in drier parts of hardwood floodplain forests on well-drained and fertile soils, mainly consisting of *Quercus robur*, *Carpinus betulus*, *Ulmus minor* and alien *Ailanthus altissima* (Essl et al. 2003, Terwei et al. 2016). Dry deforested slopes in Czechia were stabilized using *Robinia* and locally alien *Pinus nigra* at the turn of the 19th century.

The environmental impact of *Robinia* growing in mixed stands is considerably less than in monocultures. In closed mature forests, it survives only as individual trees or groups of trees in areas that were previously disturbed. The composition of shaded undergrowth is dependent on the proportion of the canopy that consists of *Robinia* (Essl et al. 2011). Birds benefit from its presence in mixed forests up to approximately equal proportions between *Robinia* and native trees, but its higher share causes shifts in bird community compositions toward a dominance of generalist species at the expense of specialists. This invasive species affects birds by altering structural components of the habitat and related supply of food and cavities for hole-nesting birds (Kroftová and Reif 2017). Mixed *Robinia* forests occur mostly close to native forests and thus *Robinia* does not pose danger for local or surrounding vegetation.

Establishment and maintenance: Reasons for the establishment of these forests were either to supplement natural sparse stands, e.g. forest-steppes with *Quercus* spp. or to improve soil quality, yield and species diversity after logging of native forests and in inter-cropping plantations (Figure 3B; Groninger et al. 1997, Mosquera-Losada et al. 2012). Mixed forests with *Robinia* can be managed as a standard part of current silviculture if some conditions are fulfilled. It is important to reduce light availability inside the forest. Traditional management with regular clear-cuts recurring every 20–30 years creates sunny sites which are suitable for reproduction and vegetative regeneration of *Robinia* and thus drives its invasion into native deciduous forests (Radtke et al. 2013). Such invasion can be accompanied by spread of other weedy or invasive species. Natural disturbances forming light gaps in closed forest canopies, such as trees

dying, fire or windthrow are other factors facilitating *Robinia* invasion as the species is highly adapted to disturbance. Under unfavourable light conditions, it develops a persistent bud bank on roots, stems and branches, allowing a rapid reaction to canopy opening following disturbance resulting in the establishment of compact clonal colonies covering areas up to several hundred square meters (Kowarik 1996, Chang et al. 1998, Krízsik and Körmöczi 2000, Schiffleithner and Essl 2016).

Tolerance of natural succession: Natural decline in *Robinia* abundance during succession was observed only in forests without large-scale disturbances, where *Robinia* finally occurs only as an admixture restricted to more open sites (Motta et al. 2009, Somodi et al. 2012, Terwei et al. 2013).

Conversion: Selective cutting that reduces light availability (Radtke et al. 2013) and favours native tree species is needed in such mixed forests. However, efforts to eradicate all *Robinia* trees would be fruitless because of economic demands and risk of failure.

3. Unmanaged old *Robinia* forests (Table 2, Figures 2, 3C)

Protective monodominant forests 12–16 m tall and over 50 years old on steep slopes pose a big problem in terms of their stability. Trees gradually die, are prone to windthrow and damage and the forest becomes more open. The shrub layer is rich in species. The herb layer consists of dominating grasses, relicts or pioneers of natural forest communities and nitrophytes with cover depending on water regime of topsoil. Such protective forests provide excellent honey (Vítková et al. 2017).

Establishment: In some countries (e.g. Czechia and Switzerland), this species was used to stabilize deforested steep eroded hillsides along rivers that were threatened by soil erosion (former pastures) and transport corridors (Vítková et al. 2017). Because of inaccessible terrain, old *Robinia* plantations have remained without management for several decades.

Maintenance: Maintenance or restoration with native species is mostly not profitable. Old trees are often unstable, therefore logging is difficult and risky, and profit is low. Moreover, logging may trigger soil erosion and regeneration of *Robinia.*

Tolerance of natural succession: During spontaneous succession, *Robinia* is replaced by shade-tolerant competitive trees such as *Fraxinus excelsior*, *Acer pseudoplatanus*, *A. platanoides*, *A. campestre* (Figure 3C) or tall shrubs such as *Crataegus monogyna* on dry sites (Vítková 2014). The rate of this succession is greater if populations of native competitors already occur in the understory or in the neighbourhood. Under closed canopies of native species, *Robinia* does not sprout spontaneously or only slightly (Vítková et al. 2016).

Conversion: Slow conversion to natural forest by means of natural succession is recommended, if there is no risk to biodiversity (adjacent natural habitats) or human infrastructure (traffic corridors or built-up sites; Pergl et al. 2016b). To prevent recovery of *Robinia,* it is important to avoid all interventions that induce sprouting, even leaving dead wood at a site after disturbance (e.g. wind break). If necessary to proceed faster,

the natural step-wise canopy opening can be supported by killing of vital trees using combination of cutting and incomplete girdling deep into the phloem followed by application of herbicides (Böcker and Dirk 2007). Very slow decay of felled *Robinia* trunks (Schwarze 2007) may be utilized to stabilize slopes. However this is costly and time-consuming and should be used only when other methods or natural succession fail.

4. Stands in human-made habitats (Table 2, Figures 2, 3D)

A common feature of this rather heterogeneous type is a ruderal environment in urban, agrarian, industrial or mining areas (Figure 3D), and a high proportion of aliens including cultivated ornamental woody species in the canopy or understory. The stands are widespread across Europe and differ in their origin (spontaneous vs. planted), structure (forest vs. shrubs or semi-open stands) and composition (pure or mixed stands with different types of undergrowth). Most stands are young with either prevailing isolated tree clumps or strips growing in the peripheries of towns and agrarian landscapes or larger disconnected groves in reclaimed mining areas.

Establishment and tolerance of natural succession: As early as in the 1970's, *Robinia* was used for the biological recultivation of the post-mining landscapes and landfills (e.g. Bellon et al. 1977) as it is still used in many countries in Europe, South Korea and China (Kim and Lee 2005, Grünewald et al. 2009, Wang et al. 2012, Wojda et al. 2015). In mining areas e.g. in Poland, Germany and Czechia, *Robinia* forms planted or spontaneous stands with native pioneer species such as *Betula pendula*, *Pinus sylvestris*, or alien *Populus* hybrids. In urban areas, *Robinia* is at first cultivated, often escapes and overgrows wasteland and public greenery. These *Robinia* stands are accompanied by native nitrophilous trees such as *Acer platanoides* and *Fraxinus excelsior,* and many aliens such as *Prunus cerasifera, Lycium barbarum* and *Parthenocissus quinquefolia*. In agricultural Pannonian lowland, spontaneous and planted *Robinia* stands along roads are commonly admixed with thermophilous alien trees such as *Ailanthus altissima*, *Gleditsia triacanthos*, *Celtis occidentalis* and *Morus alba*.

Maintenance and conversion: Active management is needed since rapid spontaneous changes tend to occur in this habitat. Consideration of the local context (e.g. role of surroundings, ornamental or utility value, claims of owner or public) is necessary, especially in urban areas. Therefore, different parts of the same stand may be managed differently, including e.g., removal of *Robinia* or whole stands. However, there is no reason for eradicating or banning the planting of *Robinia* in urban areas (Sjöman et al. 2016). Some stands with alien species can even be developed within a novel system of urban nature (e.g. in Berlin; Kowarik and Langer 2005). Planting *Robinia* in mining areas does not pose a problem providing its dispersal does not threaten surrounding valuable habitats. Its gradual decrease during natural succession or mechanical control followed by conversion of stands to vegetation with native species is recommended.

5. Dwarf *Robinia* stands growing in natural grasslands (Table 2, Figures 2, 4A)

Most of these stands originated from unsuccessful planting combined with spontaneous spread in dry habitats. *Robinia* survives in very dry habitats where it occurs as small and twisted trees (~5–10 m in height) or even shrubs forming sparse semi-open stands with an admixture of native xerophilous shrubs, e.g. *Crataegus* spp., *Prunus spinosa* and *Rosa* spp. This type is common in the Pannonian lowland (Hungary and adjacent parts of Austria, Czechia, Slovakia and Slovenia) and in Southern and South-eastern Europe.

Establishment and tolerance of natural succession: In some European countries (e.g. Slovakia, Slovenia, Italy), there is a long historical tradition in *Robinia* planting for vineyard poles and wine barrels (at least since the late 19th century; Vítková et al. 2017). Such plantations have been established at sunny and dry sites of low quality – often low stony knolls surrounded by farmland, where ploughing of fields or mowing of meadows have prevented the vegetative spread and survival of *Robinia* seedlings and sprouts (Figure 4A). Slow growth and propagation of *Robinia* together with weak nitrification and low shading effect ensure the survival of these stands and of some plants, fungi, invertebrates and birds of sunny habitats (Vítková and Kolbek 2010, Ślusarczyk 2012, Hanzelka and Reif 2015b). Such stands form stable patches increasing the local biodiversity of deforested land; with some of them having over 60 species/200m^2. Some rare plant species are specifically linked to these stands, such as perennial grasses (*Melica ciliata, M. transsilvanica*), geophytes (*Anthericum liliago, Ranunculus illyricus,* many species of *Allium, Gagea, Muscari*, and *Ornithogallum* genera) and xerophilous herbaceous plants (*Hesperis tristis, Verbascum phoeniceum*). Despite high levels of potential nitrification, nitrophytes typical of *Robinia* stands occur only rare, probably due to drought (Vítková et al. 2015).

Maintenance and conversion: It should be left to the nature conservationists to decide whether to tolerate or remove these stands. However, most of these stands are very old and unlike those in mesic habitats, their shrubby growth does not indicate they are young plants with a potential for future growth, but are usually full-grown with their propagation greatly constrained by stress (Vítková et al. 2017). As in previous units, eradication of *Robinia* and restoration of native vegetation would be expensive and very risky. Monitoring succession and restricting spread into surrounding habitats, possibly combined with grazing or mowing seems to be the optimal management strategy.

6. Young *Robinia* stands spreading into vulnerable habitats (Table 2, Figures 2, 4B)

This type, which complements the previous one, refers to current invasion of natural habitats by *Robinia* (Figure 4B). Spontaneous occurrence of the young stages of *Robinia* poses serious threat to the conservation of dry to mesic grasslands and open dry forests as they are the habitats most endangered by this species invasion (Vítková et al. 2017).

Establishment and tolerance of natural succession: Compared to native trees, *Robinia* has a high sprouting ability and is extremely resistant to disturbance. It produces

Figure 4. Non-forest habitats (**A–C**) and *Robinia* in urban environment (**D**). **A** Agrarian landscape with small-scale and semi-open *Robinia* stands. The spread of this species is suppressed by regular use of farming practices **B** Root suckers of *Robinia* invading a thermophilous grassland, which is the habitat of protected plant species **C** Intensive short rotation plantation regenerated by coppicing **D** Avenue of flowering *Robinia* in Prague (Czech Republic).

numerous root suckers that enable it to disperse at up to 1 m per year (Central Europe; Kowarik 1996) or 2 m per year (South Europe; Crosti et al. 2016) in non-forest ecosystems. Especially after disturbance of a tree its roots produce sprouts that grow up to 4m in height per year. On shading by *Robinia* the light regime, microclimate and soil conditions change and endangered light-demanding plants and invertebrates disappear (e.g. Kowarik 1994, Greimler and Tremetsberger 2001, Matus et al. 2003, Vítková and Kolbek 2010). Based on above mentioned reasons, it is not possible to tolerate establishment of *Robinia* plantations and their natural succession on vulnerable habitats, especially dry to mesic grasslands (including sandy steppes and rocky outcrops) and open dry forests as well as areas within a radius of 500 m from them (consistently with http://neobiota.bfn.de).

Maintenance and conversion: The spread should be restricted if *Robinia* stands occur in or adjacent to fallow land, grassland or other habitats with rare native plants, such as those on rocky slopes. The eradication should be rapid and persistent although expensive and risky due to use of herbicides and the disturbance causing vigorous regeneration of *Robinia* and erosion resulting in the release of nutrients and growth of weeds. For detailed list of suitable and unsuitable methods see (Silva et al. 2014, Schmiedel et al. 2015, Pergl et al. 2016b). However, no universally efficient and widely acceptable method seems to exist, because the stem- and root-sprouting ability of *Robinia* is affected by the eradication method as well as by local site conditions. Application of herbicides is necessary, otherwise resprouting of *Robinia* overcomes the effect of grazing or mowing and suckers appear even 30 years after the felling of *Robinia* (Trylč 2007).

Whole *Robinia* clones must be removed as the roots of the individual plants are connected. For quick eradication the best choice is felling followed immediately by spraying the area felled with herbicide. Removal by incomplete girdling (Böcker and Dirk 2007, Schiffleithner and Essl 2016), though demanding and time-consuming, is suitable for inaccessible sites. It is more efficient if combined with herbicide application at the end of summer, when assimilates are translocated to the roots. Elimination of new suckers and seedlings is necessary for at least 3–5 years. Well-proven is long-term grazing by goats once or twice a year, which also prevents the spread of tall weedy grasses. It is also best to remove all the *Robinia* biomass in order to prevent its sprouting and nutrient release. Due to the high dispersal rate of *Robinia*, control should also concentrate on populations adjacent to valuable habitats, at least to the distance of 500 m (consistently with http://neobiota.bfn.de).

7. Intensive short rotation plantations (Table 2, Figures 2, 4C)

Planting short-lived *Robinia* plantations for renewable bioenergy production (Figure 4C) is currently fashionable. Short-lived *Robinia* plantations occur in many countries worldwide, such as Albania, Austria, China, Italy, Germany, Greece, Hungary, Poland, Slovakia, Spain, South Korea and the United States (e.g. Grünewald et al. 2009, Rédei and Veperdi 2009, Stolarski et al. 2013, Zhang 2014, Straker et al. 2015). Other forms of

utilization are rare, for example forage (Papanastasis et al. 1998). Energy production is profitable due to its high, early and easily produced dense, fast drying and combustible wood (Rédei et al. 2008). In the reclamation of heaps of industrial waste in post-mining landscapes one can add other benefits of using *Robinia,* such as high drought tolerance and ability to fix nitrogen (Grünewald et al. 2009).

Establishment and maintenance: These plantations should be established only in areas where an abundant metapopulation of *Robinia* already exists. The most common methods are either planting seedlings or rooted cuttings, however, a more environmental friendly and cheaper method is to transform *Robinia* forests at low quality sites (Rédei and Veperdi 2009). Because of its short coppicing period (average 4–5 years), *Robinia* grows to 5–6m in height (Rédei et al. 2010), nutrients in topsoil are depleted (Vasilopoulos et al. 2007) and undergrowth is species-poor and dominated by undemanding weeds. It is important to prevent further spread of *Robinia* (Crosti et al. 2016). Although closed forests are invasion-resistant, the establishment of new plantations in open land, especially at abandoned sites, close to roads or navigable rivers, is not recommended. As a barrier against *Robinia* invasion buffer zones of non-invasive plants (e.g. vineyards, orchards or fields) can be used, because periodic ploughing or harrowing suppress both the vegetative and generative reproduction of *Robinia* (Crosti et al. 2016).

Tolerance of natural succession and conversion: Extreme caution should be taken when such plantations are abandoned. There is a great risk of an intensive growth of suckers of *Robinia*, especially as the spontaneous succession of native vegetation is very slow. In northeastern Greece, succession to near natural riparian forest was not recorded even 14 years after abandonment. Site preparation for establishment of plantations as well as relatively low production of litter and periodic removal of organic matter through wood cutting caused a long-term changes in availability of soil nutrients and light, thereby affected species composition in behalf of ruderal species (Vasilopoulos et al. 2007). Another limitation often is a low pool of native trees in the vicinity and lack of serious natural enemies (Vítková et al. 2017). For successful conversion it is important to eliminate competition from *Robinia* and assist with reforestation using native tree species.

8. Cultivated single trees and avenues (Table 2, Figures 2, 4D)

This type includes individual *Robinia* trees occurring solitarily or in groups in parks, gardens and at sites such as chapels or crossroads (Pergl et al. 2016d), furthermore in lines along roads, streets and rivers, in windbreaks, vineyard boundaries, hedgerows, gullies etc. (Figure 4D). Their function is mainly ornamental, together with protection against dust, noise or wind. Such structures are currently used to protect crops and livestock against weather extremes, for example in Hungary (Takács and Frank 2009). In Germany, "open orchards" consist of belts of vegetables or cereal fields separated by lines of fast-growing trees including *Robinia*, which are coppiced for biomass production and also used for improvement of soil quality and biodiversity (Mosquera-Losada et al. 2012, Medinski et al. 2014). As *Robinia* is a favourite horticultural tree, there are

many interesting cultivars that are generally less invasive than the typical form (Hillier and Lancaster 2014).

Establishment, maintenance, tolerance of natural succession and conversion: Planting is usually easy. Trees need to be pruned and suckers removed regularly to prevent invasion into surrounding habitats. Consideration of the local context is necessary, *Robinia* should not be planted close to vulnerable natural habitats. Old trees are desirable because they provide shade and habitat for, e.g., rare saprophytic fungi or saprophagous beetles (Ślusarczyk 2012, Stejskal and Vávra 2013).

Conclusions

Based on the environmental conditions and human land use we reconcile the main contradictory approaches to *Robinia pseudoacacia* in Europe, where it is planted for multiple beneficial purposes, but also escapes from cultivation and becomes invasive, with impact on species diversity and ecosystem functioning. At the moment the management of *Robinia* stands varies locally, depending on the socio-economic benefits vs. biodiversity impacts, from enthusiastic embrace to planting restrictions to complete rejection. Unfortunately, the information sources related to possible management are biased by narrow focus of the parties involved (environmental vs. forestry). Furthermore, the legislation in several European countries governing the management of *Robinia* is often contradictory.

For these reasons, an integrated solution to harmonize the different views of various target groups is needed. We propose a stratified approach to the *Robinia* management, which takes into consideration both the ecological and economic aspects associated with its occurrence. Because *Robinia* grows in a wide range of habitats ranging from urban environment and agricultural landscape, to forest and natural grassland, neither unrestricted cultivation nor large-scale eradication is feasible. We offer several decision scenarios suitable for specific situations in particular landscapes, where *Robinia* is tolerated in selected areas, but eradicated in others. We distinguish eight types of *Robinia* stands; for each of them we describe ecological conditions, economic benefits, and environmental risks and propose sustainable management practices.

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